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ЕКСПЕРИМЕНТАЛНО И ТЕОРИСКО ИСТРАЖУВАЊЕ НА ЕФЕКТИТЕ ОД СПРЕГАЊЕТО НА ЧЕЛИКОТ И БЕТОНОТ КАЈ КОНТИНУИРАНИ НОСАЧИ ОД МЕЃУКАТНИ КОНСТРУКЦИИ

РЕЗИМЕ

Спрегнатите конструкции , сами по себе, претставуваат една комплескна целина на спој од двата најупотребувани материјали во градежништвото, бетонот и челикот. Подлежат на комплексни анализи за однесувањето на двата материјали и средствата за спрегање - можданиците. При анализа на ваквите конструкции потребно е познавање од карактеристиките и однесувањата на двата материјали, и познавање од однесувањето на конструкциите како целина. Со цел да се добијат подетални податоци за ефектите од спрегањето на челикот и бетонот кај континуираните носачи изработена е експериментална програма која се состои од испитувања на повеќе елементи и носачи.

Клучни зборови: спрегнати конструкции, спрегнати плочи, можданици, челични конструкции

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EXPERIMETAL AND THEROETICAL RESEARCH OF THE EFFECTS OF COMPOSITE STEEL AND CONCRETE STRUCTURES FOR CONTINUOUS BEAMS

SUMMARY

The composite steel and concrete structures, as they are, are complex unity of the two of the most utilized materials in civil engineering, steel and concrete. For these kinds of structures, a complex analysis is needed for the behaviour of the steel, concrete and the shear connectors. The analysis of such structures requires knowledge of the characteristics and behaviour of both materials, and knowledge of the behaviour of structures as a whole. But to have a real picture of the realistic behaviour there is need for research, which represent the core knowledge in the modern civil engineering. In order to obtain further data on the effects of composite steel and concrete structures for continuous beams, an experimental program was made with multiple elements and beams.

Key words: composite structures, composite deck, shear connectors, steel structures

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1. INTRODUCTION

The experimental program was conducted from several testing procedures. First, a modified test sample was made for testing the nonlinear behaviour of the shear connectors, which through experimental research the P-d diagram was obtained, required for the research of the beams.

Experimental and theoretical research is carried for two simple beam girders with span of 5.04m, for testing of the ultimate limit state and behaviour of the adopted cross-section through the cycles of loading.

With the adopted cross-section a model of theoretical and experimental research of continuous beams with two spans of 5.75m was made. The beam was tested with cyclical and successive loads until the ultimate limit state of the cross-section at the bearing. The beam was tested for impact analysis comparison for preloading through controlled deformations.

Comparison was made from the results of the testing with the analytical models according to EN 1994, and 3D models with "solid" finite elements with defined behaviour of the model as close as it can to the tested beams.

2. METHOD OF TESTINGS

The testing is carried out for obtaining relevant data on the behaviour of the pre-stressed by imposed deformation composite continuous beam, and to obtain comparative results to continuous composite beams, especially at the support.

2.1. Testing the materials

After every casting of the concrete a sample was taken for testing the strength of cubes with dimensions 150x150x150mm, and cylinders with dimensions 150x300mm. The modulus of elasticity was tested on three cylinders for each casting. Also, the shrinkage of each cast concrete is measured with three prisms within 175 days for the first beam, and 157 days for the second beam. The adapted strength class of concrete for the two beams is C25/30 according to EN 1992.

The testing of compression and tensile strength for the concrete for the first beam was made on the 29th and the 32nd day from casting. The compression strength of cube is $f_{ck,cube}$=36.64MPa (+22.1%), the strength of cylinder is f_{ck}=29.51MPa (+18.0%). The tensile strength of the concrete for the first beam is f_{cm}=2.95MPa (+13.5%), and the modulus of elasticity is E_{cm}=31.97GPa (+3.1%). The shrinkage at the 29th day (the day for the testing of the first beam after the casting) is measured with value of 0.255‰. The calculated value of the shrinkage in accordance with EN 1992 is 0.230‰ (-10.9%).

For the second (pre-stressed) beam, the obtained values from the testing of the concrete are $f_{ck,cube}$=32.03MPa (+6.8%, with standard deviation of σ=1.79), f_{ck}=31.65MPa (+26.6%), f_{cm}=2.97MPa (+14.2%) and E_{cm}=31.65GPa (+2.1%). The measured shrinkage on the 34th day (the day for the testing of the second beam after the casting) is 0.241‰. The calculated value of the shrinkage in accordance with EN 1992 is 0.273‰ (+13.3%).

The yield strength, the tensile strength and the maximum elongation of a representative sample of the shear connector material, steel beam, reinforcement and steel sheeting is determined.

The reinforcement steel is class B, in accordance with EN 1992-1-1, Annex C, table C.1 and C.3N, with yield strength of f_{yk}=597N/mm^2, tensile strength f_{uk}=662N/mm^2, with $k=f_{uk}/f_{yk}$=1.11, and ε_{uk}=9.9%.

The steel for the headed studs is class S235J2+C450, in accordance with EN 13918, with yield strength f_y=502N/mm^2, tensile strength f_u=552N/mm^2, with $k=f_u/f_y$=1.10 and δ_5=18.5%.

The steel for the steel sheeting deck is class S550GD Z275, in accordance with EN 10147, with yield strength f_y=675N/mm^2, tensile strength f_u=770N/mm^2, with $k=f_u/f_y$=1.14 and δ=24.6%.

The steel for the beam is S275JR, in accordance with EN 1993, with yield strength f_y=275N/mm^2, tensile strength f_u=424N/mm^2, with $k=f_u/f_y$=1.54 and ε_u=18.9%.

The results from the testing of the steel (reinforcement, headed suds, steel sheeting and steel beam) meet the requirements from EN 1992 and EN 1993.

The same class of the steel for reinforcement, headed studs, steel sheeting and beam is used for the two composite continuous beams.

2.2. Modified test on shear connectors

The three samples for the modified (specific) testing of the behavior of the shear connectors are tested in the same environment, with the same testing equipment and testing conditions.

The testing is carried out according to EN 1994, with cycled loading with first step of loading from 0% to 40%, then 25 cycles of loading from 5% to 40%. After the cycled load, the samples were loaded until failure in time not less than 15 minutes.

For the need of the testing, measuring and loading equipment is used. The load is applied through 100 ton press where the force is regulated with electronic dynamometer. The longitudinal slip between the steel and the concrete is measured with 3 electronic comparators. The transverse separation between the concrete slab and the steel section is measured with 4 electronic and 4 dial comparators. The accuracy of the testing equipment is in the range of ±1.5%.

The electronic equipment is connected to HBM Quantum data acquisition system amplifier with direct connection to computer. The measuring of the electronic equipment is carried out through the whole testing in real time.

In table 2 the results from the testing of the three specimens are given with the measured strength of the force of failure ($P_{Rk,U}$), and the analyzed values of the strength of one headed stud.

Specimen	P_{Rd} [kN]	$P_{Rd,U}$ [kN]	age of conc [days]	$P_{Rk,U}$ [kN]	P_{Rk} [kN]	f_u/f_{ut}	$P_{Rd,(1)}$ [kN]	difference [%]	$P_{Rd,D}$ [kN]
П 1	51.61	516.10	34	602.86	542.57	0.996	54.04	+4.71	51.84
П 2			35	561.82	505.64		50.36	-2.42	
П 3			38	578.02	520.22		51.81	+0.39	

Table 2. Results from the testing

Where:

- P_{Rd} is design resistance of one stud including the partial safety factor
- $P_{Rd,U}$ is ultimate design resistance of eight studs, without the partial safety factor
- $P_{Rk,U}$ is ultimate design resistance of eight studs from the testing
- P_{Rk} is reduced ultimate design resistance of eight studs from the testing, according to EN 1994-1-1, B.2.5, $P_{Rk}=0.9\cdot P_{Rk,U}$
- $P_{Rd,(1)}$ is design resistance of one stud including the partial safety factor from the testing
- $P_{Rd,D}$ is design resistance for the stud from the three specimens, statistical evaluated from all the results in accordance with EN 1990, Annex D.

The difference in negative resistance of -2.42% is in the range of the accuracy of the testing equipment of ±1.5%. The deviation of the results from the three specimens is not bigger than 10%, and with the design value of $P_{Rd,D}$ =51.84kN>P_{Rd}=51.61kN, can be concluded that the headed studs meet the requirements given in EN 1994.

In figure 1.a, 1.b and 2.a. the determination of the slip capacity from the “P-δ” diagram for one headed stud are given, where $P_{Rk,(1)}=0.9 \cdot P_{Rk,U,(1)}$ is reduced ultimate design resistance from the testing for one headed stud. From the value of $P_{Rk,(1)}$ and the “P-δ” diagram from the testing, the value of the slip capacity “δ_u” can be determined as given in figure 1 and 2.

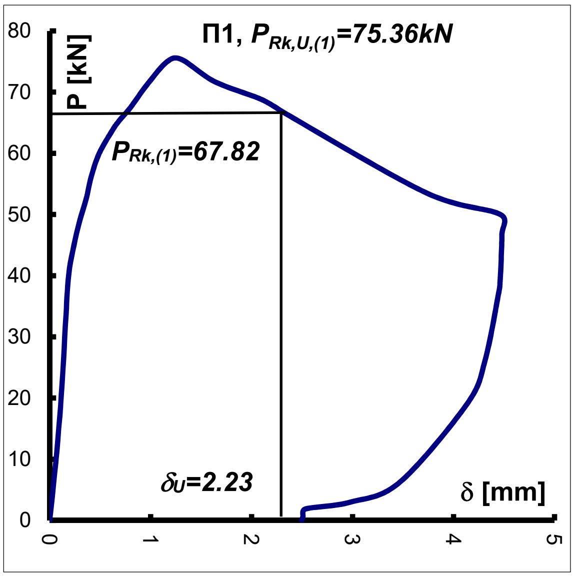

Figure 1.a. “P-d” diagram, specimen П1, slip capacity determination

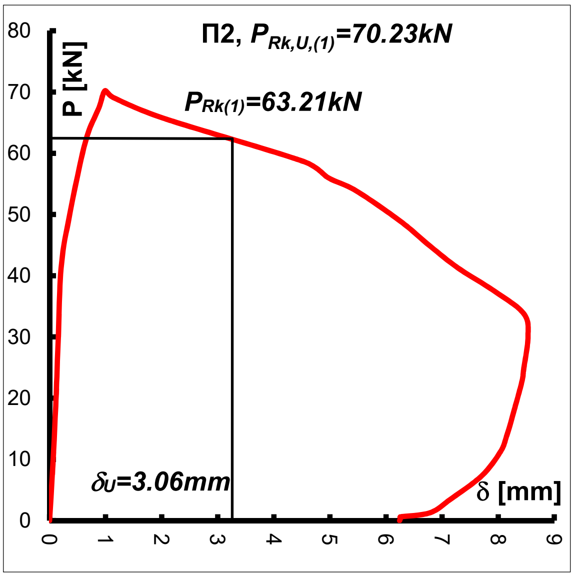

Figure 1.b. “P-d” diagram, specimen П2, slip capacity determination

In figure 2.d. the diagrams of all specimens are given, including the diagram for the analytical model (AM) obtained from the diagrams of the specimens, but in accordance with EN 1994.

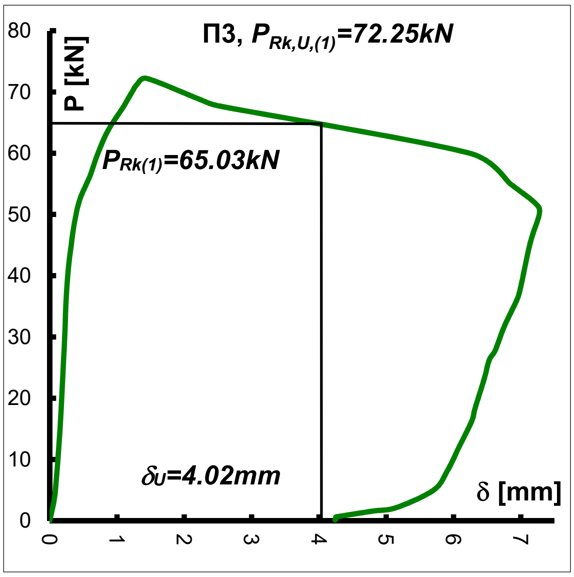

Figure 2.a. “P-d” diagram, specimen П3, slip capacity determination

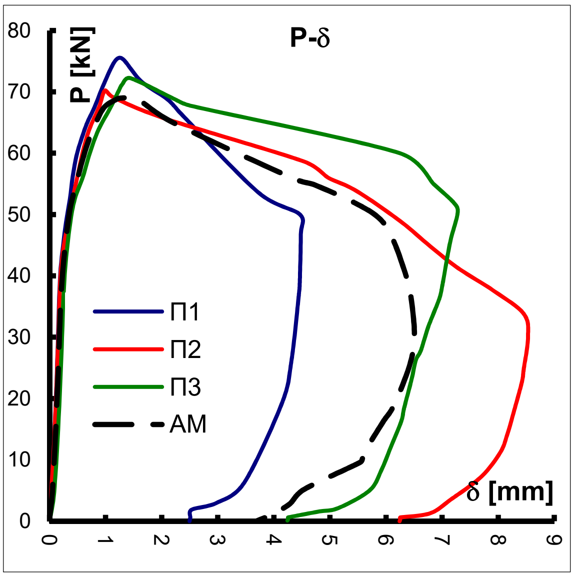

Figure 2.d. “P-d” diagram, all specimens

The values of the determined slip capacity for each specimen are 2.23mm for П1, 3.06mm for П2 and 4.02mm for П3, where according to EN 1994-1-1, Annex B, the value from all three specimens is $\delta_{uk}=0.9 \cdot \delta_{u,min}$= 2.01mm**.** Or, the value of the slip capacity from all specimens can be determined with statistical evaluation from the results in accordance with EN 1990, Annex D, in which case the value is δ_{uk}=3.17mm.

There are no significant measured values of transverse separation between the steel beam and the concrete slab.

2.3. Composite simple beam testing

The cross section of all, single span or continuous, beams is composed from IPE270 as the steel main beam, with steel sheeting from Bondeck 600 (thickness of 1.0mm) with ribs transverse to the length of the main beam, creating T-beam. The steel sheeting is connected to the beam with headed stud shear connectors, in two columns longitudinal to the main beam, where the longitudinal distance between the studs is 200mm. The studs are through deck welded to the beam in accordance with EN14555. The full thickness of the concrete beam is 52+58=110mm, as shown in Fig. 4. The concrete is reinforced with Q283 (Ø6/100mm) class B reinforcement, where above the middle support of the beam the concrete is reinforced with two layers of the same reinforcement. The composite beam is continuous with two spans of 5750mm with total length of 11500mm. The full height of the cross section is 270+110=380mm.

The load is applied through 100 ton press with two different loading cases. The first one is cycled loads with forces from 0 to 50kN as the first step, form 0 to 100kN as the second step, and from 0 to 200kN as the third loading step. After the cycled loading the load is applied in subsequent increments until failure occur, 352kN and 367kN for the two different composite single span beams.

This testing was carried out for obtaining relevant data of the behaviour and the ultimate limit state of the adopted cross section. The width of the effective activated concrete flange is measured through all steps of the application of the load, as shown in Fig. 3.

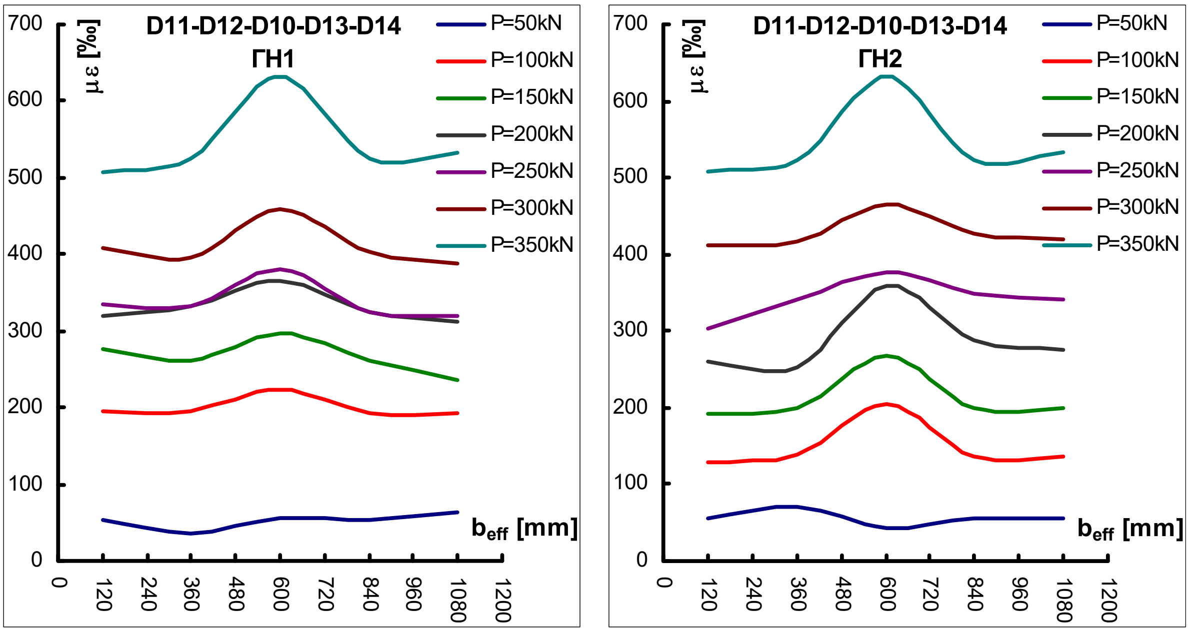

Figure 3. Activated effective width of the concrete flange, for measuring point at M_{max}

2.4. Composite continuous beam testing

The cross section is the same for all the tested beams, composed as T-beam form steel girder and concrete flange with steel sheeting as deck, shown in Fig. 4. The loading equipment is applied on the beams, as shown in Fig. 6, with the same load cycles and loading increments for the two continuous beams. For the purpose of this testing, dial and electric comparators (U1 to U102) and dynamometers (DM1, DM2) are used. Also, positioned at strategical points of interest, concrete strain gauges with length of 120mm (B1 to B7), steel strain gauges with length of 5mm (A11 to A24) are used, as shown in Fig. 7.

The load is applied through two layers of transmission beams (TL, Td, T1 to T4), where from two loading points, the load is distributed to eight loading points, simulating continuous load through the whole length of the tested beam.

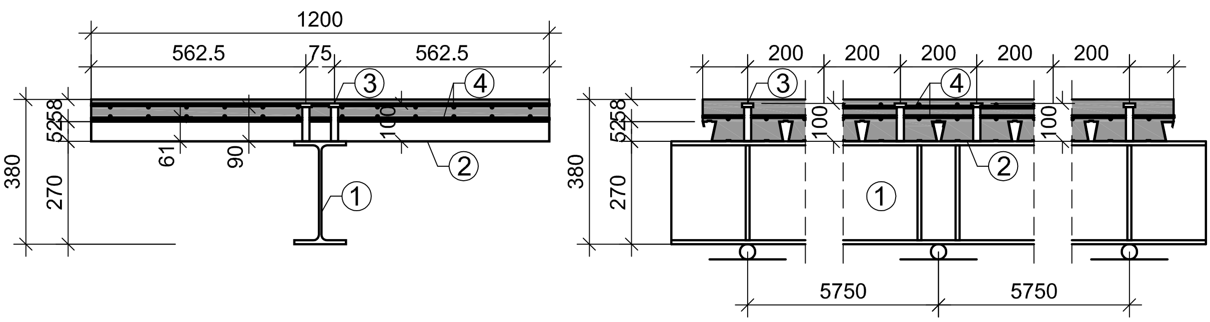

Figure 4. Cross section and testing model for the two composite continuous beams

Where:

1) main beam IPE270 (S275JR)
2) steel sheeting Bondeck 600, t=1.0mm (S550GD Z275)
3) Nelson headed stud, d=19mm, hsc=100mm (S235J2+C450)
4) reinforcement Q273 (Ø6/100mm) class B (f_y/f_u=600/660)

The composite (concrete and steel) beam is loaded with cycled load up to 40kN in dynamometer, then the load is applied in subsequent increments until failure occurs (up to 450kN). After every step of loading, values from the measuring equipment (deformeter and dial comparators) are obtained. From the electronic dynamometers, comparators and strain gauges the measurements are obtained in real time throughout the whole testing.

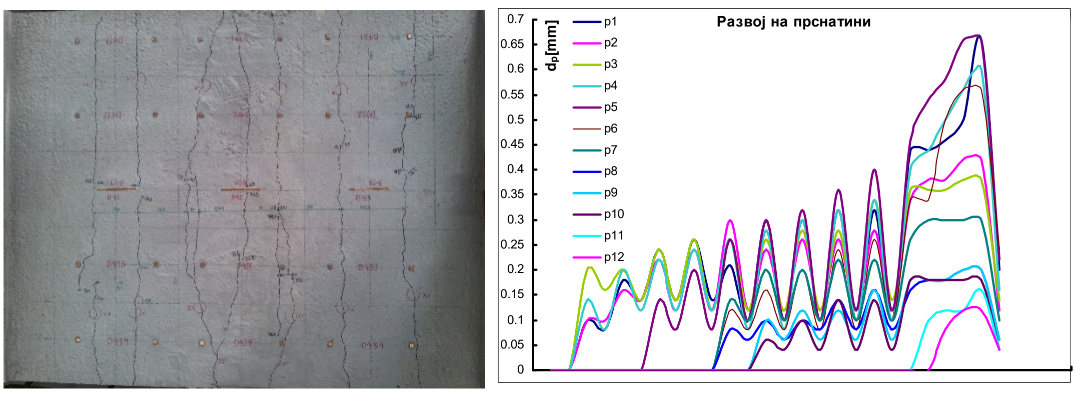

Figure 5. Cracks at support (left), development of the cracks (right)

Among all the relevant data obtained from the testing, the behaviour of the concrete flange at the support, the development of the cracks in the concrete, is observed at real time of the testing.

2.5. Testing the composite continuous beam pre-stressed by controlled imposed deformation

The pre-stressed composite beam is placed with elevation on the middle support for 18mm, and in that position the placing of the steel sheeting, the welding of the studs and the concreting were made. After 32 days of preparation and installation of the measuring and loading equipment, the beam was pre-stressed by imposed controlled deformation. After the readings from the measuring equipment at this step, the cycling loads up to 40kN was imposed, and then the load is applied in subsequent increments until failure (up to 600kN).

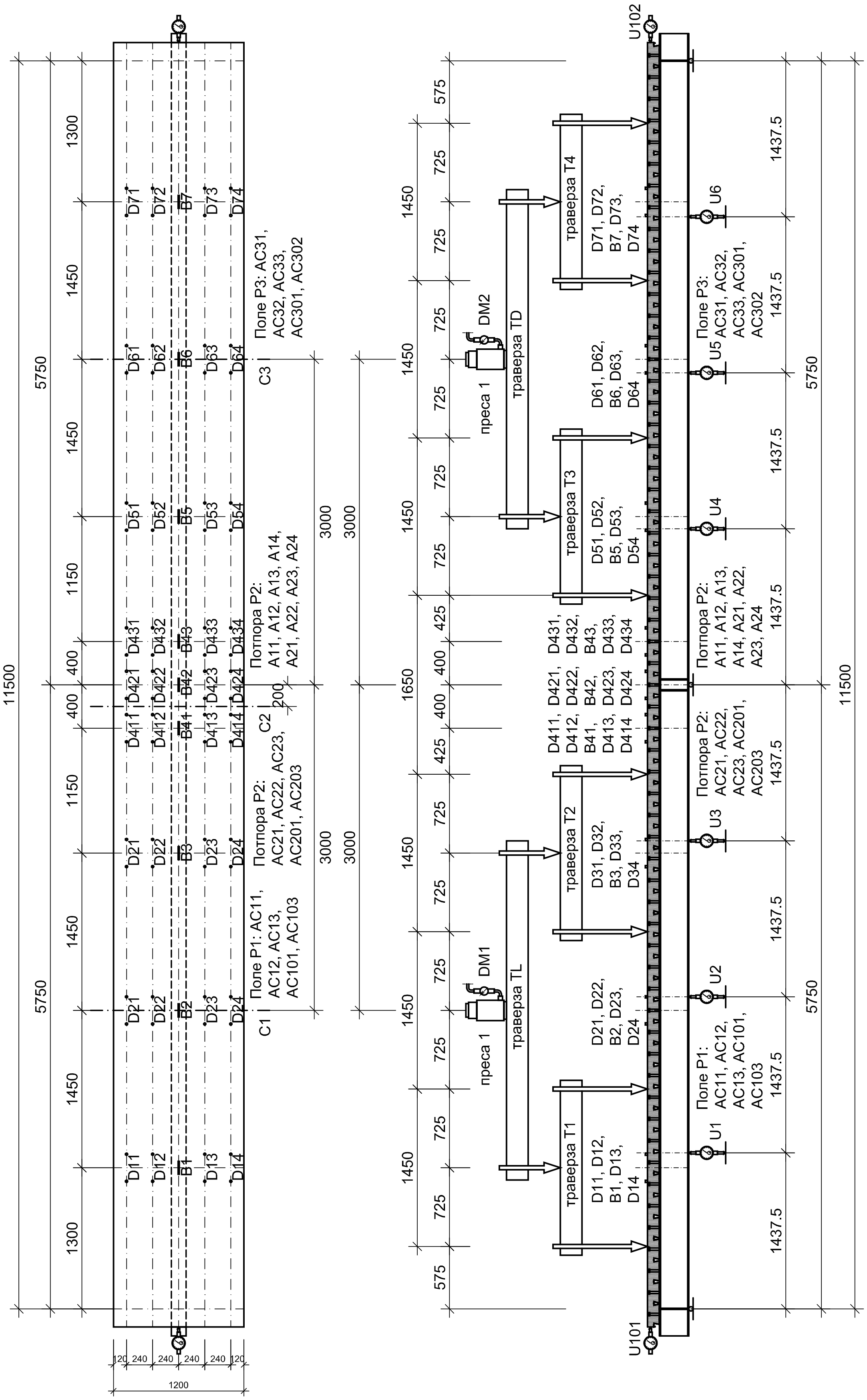

Figure 6. Disposition of the testing equipment

The behaviour of composite beam is observed, especially at the first step of the testing, the pre-stressing by controlled imposed deformation. Through the equipment, compression in the concrete slab at the support is measured. That indicates that the pre-stressing is activated and effective.

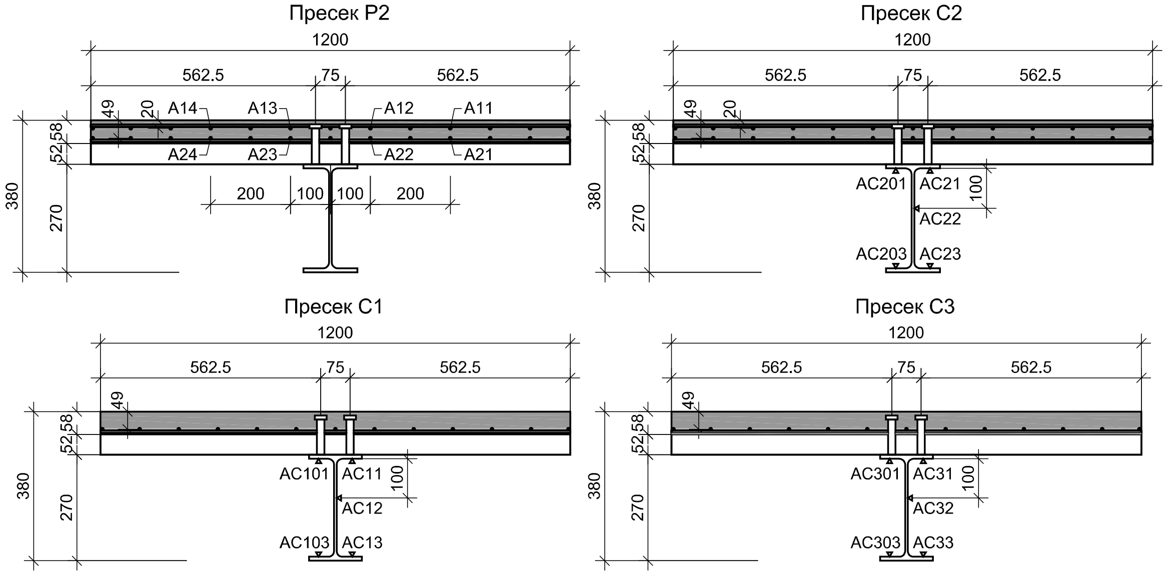

Figure 7. Strain gauges placement at characteristic cross sections

In the subsequent increments of the load, a transition from compression to tension is noticed, delaying the appearance of the initial crack. The effects of the pre-stressing are evident, as shown in Fig. 8, where the capacity, especially for the serviceability limit state, of the cross section and the beam is significantly increased.

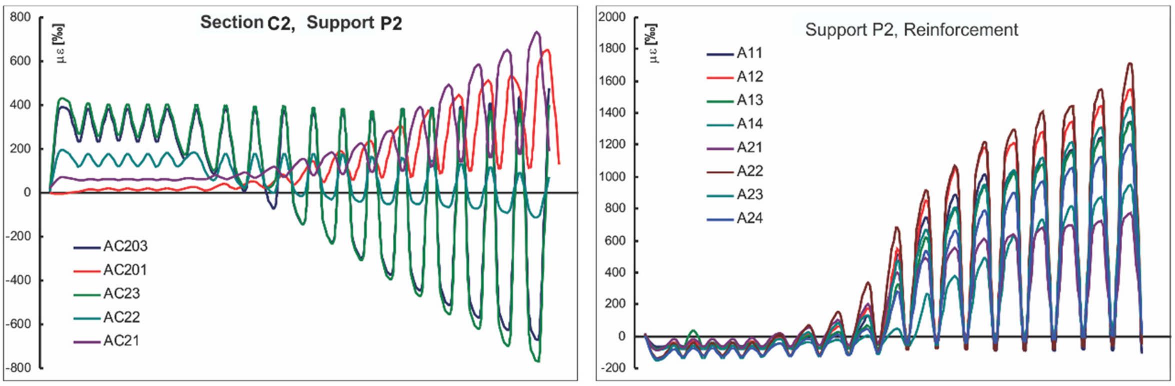

Figure 8. Effects of the pre-stressing, measured strains

2.6. Analytical models

Realistic 3D models, created with 3D solid elements and with usage of nonlinear behavior of links with defined characteristics of the used materials and elements, in software were used for comparative analysis of the testing. The shear connection between the concrete and the steel solid elements is with nonlinear link, with usage of the "P-d" diagram from the obtained behaviour of the shear studs. The nonlinear behaviour of the two different materials is defined with usage of nonlinear links between every solid element, with behaviour obtained from "σ-ε" diagrams of the tested materials.

Also, a model for comparative analysis for the tested beams was used in accordance with EN 1994, using frame elements with nonlinear analysis for obtaining only the internal forces. The frame model is with different cross section longitudinal to the composite beam.

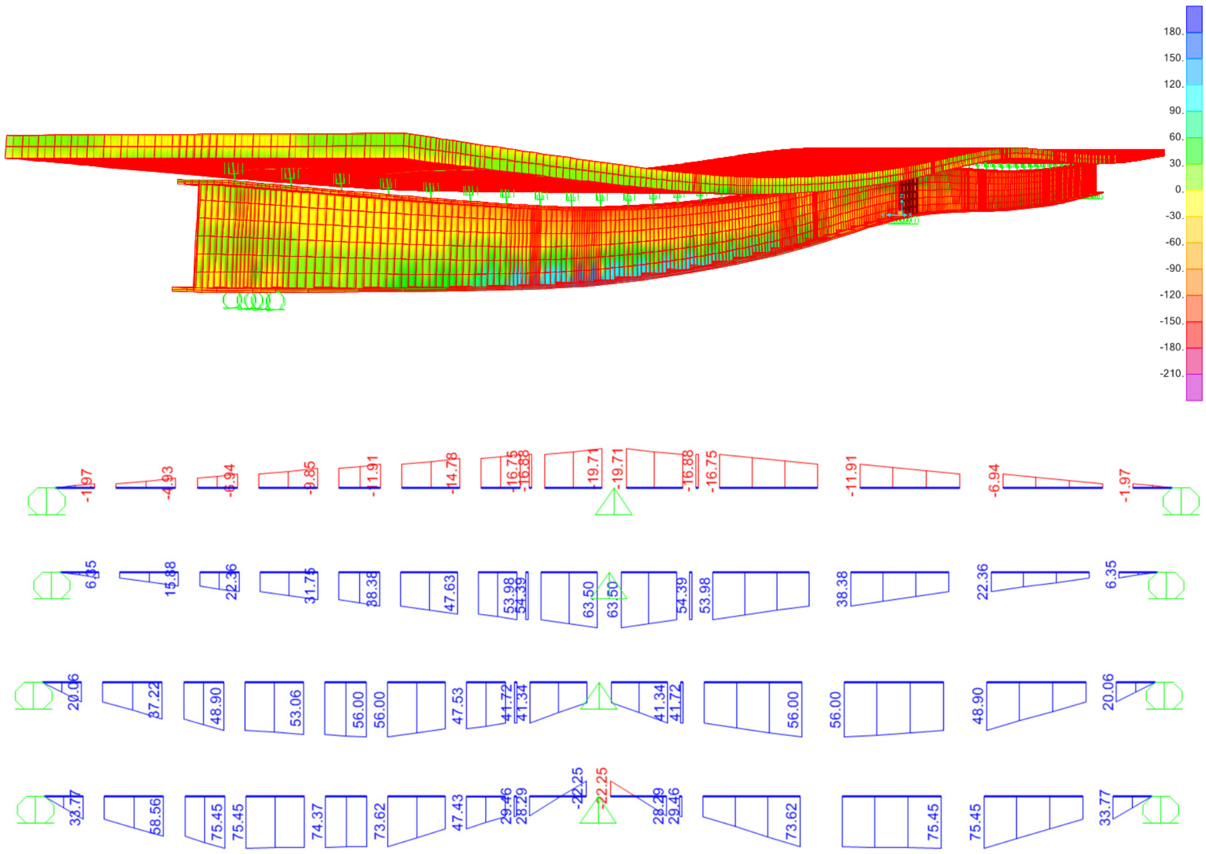

Figure 9. Analytical models, 3D realistic model (above), EC4 frame model (bellow)

3. COMPARISON OF RESULTS

All data obtained from this experimental program is processed and compared with every relevant point of interest. Additional analysis was carried out for comparison purposes between the measured results, and the different behaviour of all tested beams.

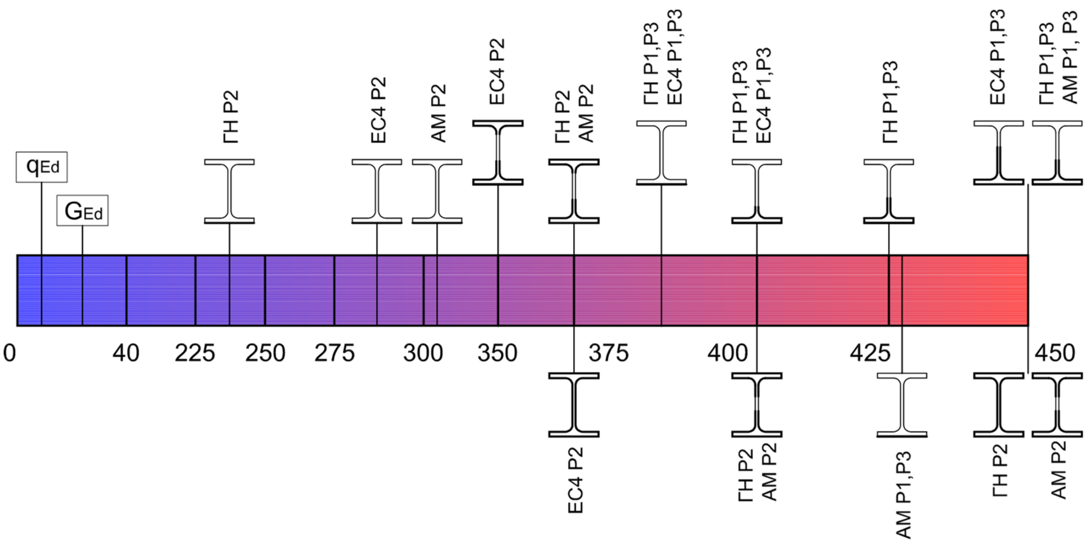

Figure 10. Results of the composite continuous beam

Also a comparison analysis was carried out for the differences between the tested model and the analytical models, including the load steps of the occurrence of the differences, the deformations, the bending moments, and the differences of the plastic behaviour of the cross section.

The main comparison of this research is between the composite continuous and pre-stressed continuous beam. All previous testing was carried out for obtaining data for the behaviour of the materials or the elements from which the beams are made.

In Fig. 10 the results from the testing and the analytical research of the first composite continuous beam is shown, where can be seen the elastic and plastic behavior of the composite beam. For instance, the first crack in the concrete is on applied load in dynamometer with value of 60kN. In loading between 225kN and 250kN the most exposed fiber at the support the yield strength of the cross section is reached. The same happens for the model analyzed in accordance with EN 1994 between 275kN and 300kN, and for “AM” just over 300kN.

First full plastification of the steel cross section is at support for the model analyzed according to EN 1994 at step of loading of 375kN in dynamometer. Full plastification of the same cross section is at step of loading of 450kN, and for “AM” just over 450kN. At the last step of loading (450kN in dynamometer) only the lower flange is plastificated for all analyzed and tested composite beams at the span. The smallest value of the elastic deflection is from the analyzed model according to EN 1994, δ_{EC4}=10.06mm then δ_{AM}=10.73mm (+6.7%) and $\delta_{ГН}$=12.14mm (+20.6% from “EC4”, +13.14% from “AM”). For the deflection with plastic behavior of the beam, the measured value for “AM” is δ_{AM}=23.20mm and for the tested beam is $\delta_{ГН}$=24.41mm (+5.2%).

From the research of the composite (steel and concrete) continuous beam, the analyzed model “EC4” is with the smallest ultimate limit state, with moment at the support $M_{Ed,EC4}$=187.06kNm, then is the tested model “ГН1” with moment at the support $M_{Ed,ГН}$=234.12kNm (+25.2%), and for “AM” the moment at the support is $M_{Ed,AM}$=254.50kNm (+36.1% from “EC4”, +8.7% from “ГН1”).

At the final step of loading value of 450kN, the internal forces at the researched beams at spans are $M_{Ed,EC4}$=232.77kNm for “EC4”, $M_{Ed,ГН}$=221.19kNm (-5.0%) for “ГН1” and $M_{Ed,AM}$=206.05kNm (-11.5% from “EC4”, -6.8% from “ГН1”).

The measured residual deflection after the unloading of the beam from the full load is δ_{PL}=7.93mm in left span and δ_{PL}=7.87mm in right span.

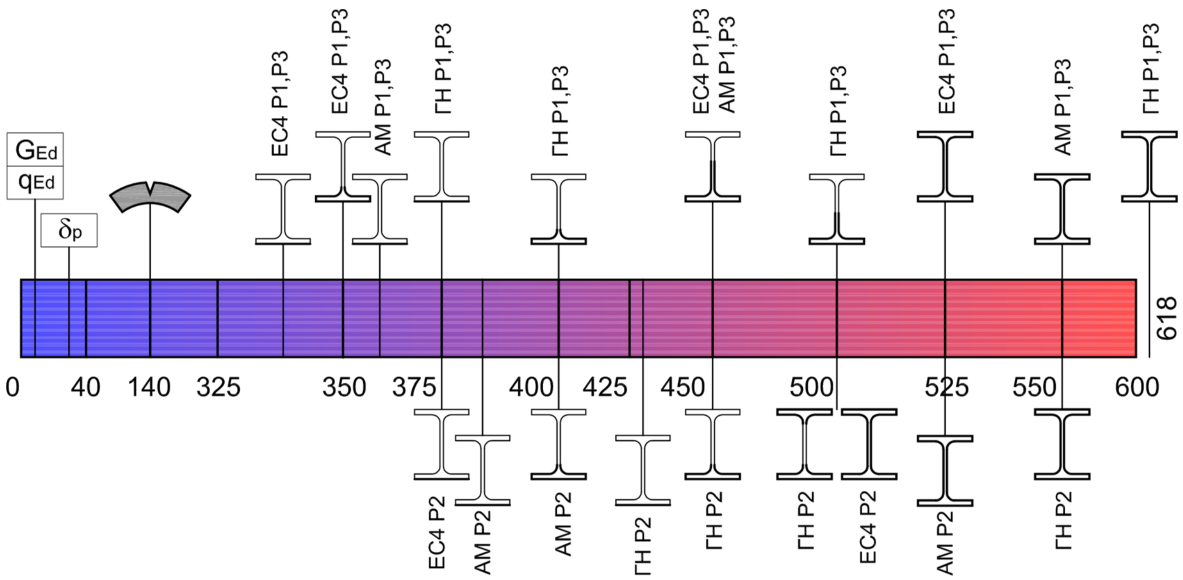

Figure 11. Results of the pre-stressed composite continuous beam

Following the logic from the previous beam, the results of the pre-stressed composite beams are given in Fig. 11, where the first crack in the concrete appears at the load step of 140kN on dynamometer. The emergence of the cracking of the concrete is delayed for 80kN in dynamometer.

The full plastification of the cross section at the support is for “EC4” at the step of loading of 500kN. The full plastification of the same cross section for “AM” is at the step of loading of 525kN, where at the same step the full plastification occurs for the cross sections at the spans for “EC4”. At the step of loading of 550kN the full plastification occurs for “AM” at P1 and P3, and at the same time for the tested model “ΓH2” at the middle support. The full plastification at spans P1 and P3 for “ΓH2”occurs at step of loading of 618kN in dynamometer.

The difference in the deformations between the analyzed and tested beams are given in figure 8. The value of the elastic deflection from the analyzed model according to EN 1994 is δ_{EC4}=13.18mm, then δ_{AM}=14.06mm (+6.7%) and measured value for “ΓH2” is $\delta_{ΓH}$=13.04mm (-1.1% from “EC4”, -7.3% from “AM”). For the deflection with plastic behavior of the beam, the measured value for “AM” is δ_{AM}=46.13mm and for “ΓH2” is $\delta_{ΓH}$=51.32mm (+11.3%).

The moment at the support according to EN 1994 is $M_{Ed,EC4}$=187.06kNm, for the tested model “ΓH2” the moment is $M_{Ed,ΓH}$=244.13kNm (+30.5%), and for “AM” the moment at the support is $M_{Ed,AM}$=254.60kNm (+36.1% from “EC4”, +4.3% from “ΓH2”).

At the final step of loading for the each researched beam, the internal forces at the spans are $M_{Ed,EC4}$=282.78kNm for “EC4”, $M_{Ed,ΓH}$=297.30kNm (+5.1%) for “ΓH2” and $M_{Ed,AM}$=284.60kNm (+0.65% from “EC4”, -4.27% from “ΓH2”).

The measured residual deflection after the unloading of the beam from the full load is δ_{PL}=25.32mm in left span and δ_{PL}=25.55mm in right span.

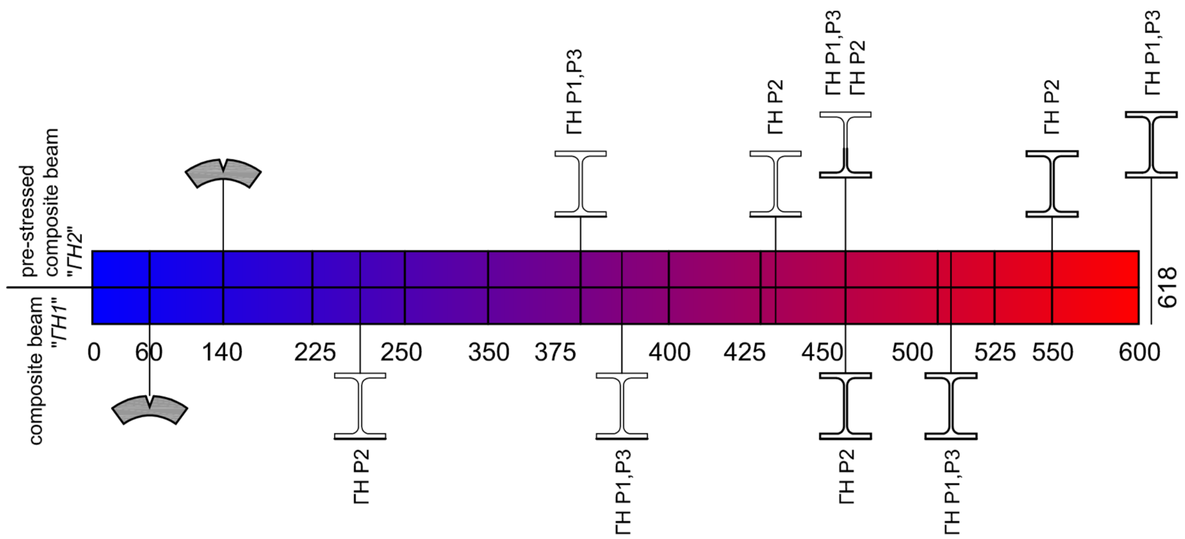

Figure 12. Comparison of the results between the composite beams

In Fig. 12 the comparison between the composite beams is made, “ΓH1” is the continuous beam, and “ΓH2” is for the pre-stressed composite beam. The different behaviour of the two beams is evident.
At first, the cracking of the concrete is delayed for 80kN in dynamometer, which is great advantage for serviceability limit state of the structure and for the elastic behaviour of the beam. According to the placement of the loading equipment shown in figure 6, the difference in the loading is about 15.4kN/m’. Also the full yielding of “ΓH1”at the middle support is at 450kN, where for “ΓH2” is at 550kN (+22.2%), where the difference in loading is about 19.3kN/m’. The approximate ultimate limit state of the composite beam at the span is at loading step of 512kN in dynamometer, where the ultimate limit state of the same cross section for the pre-stressed composite beam is at loading step of 618kN (+20.7%), with difference in loading about 20.5kN/m’.

The measured values for the last step of loading for “ГН1” (450kN) is 24.41mm, where for “ГН2” at the same step of loading is 20.12mm (-17.6%).

4. CONCLUSIONS

Having the results from the testing of the two composite (steel and concrete) continuous beam, and with the analysis of the results, some conclusions can be drawn.

There are obvious advantages of the pre-stressed composite beam. One of the advantages is the bigger serviceability limit state of “ГН2” compared to “ГН1”, where the pre-stressed composite beam can be load with additional 15.4kN/m’ until the first crack in the concrete at the middle support occurs.

In the elastic behavior of the beam, the advantages are 2.33 times higher bearing capacity than the composite beam “ГН1” until the cracking of the concrete occurs at the middle support (loading value in dynamometer from 60kN to 140kN). There is also 1.88 times higher bearing capacity after the cracks occurs until the yield strength of the most exposed fiber is reached. The pre-stressed composite beam “ГН2” has 20.7% (20.5kN/m’) higher ultimate limit state than the composite beam “ГН2”, which means that the pre-stressed beam can be load with additional 20.5kN/m’ until the ultimate limit state is reached. Also, the deflection of the pre-stressed composite beam is for 17.6% lesser.

It can be concluded that with pre-stressing the composite beam, by controlled imposed deformation (deflection of the middle support) by 18mm, there are many advantages of the behavior of the beam compared to (ordinary) composite beam.

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